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IMPORTANCE OF ANISOTROPIC COEFFICIENTS FOR MATERIAL CONSTITUTIVE MODELS IN FORMING AND CRUSHING SIMULATIONS

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ABSTRACT

The unique material properties of aluminium material have gained more attention in automotive and aerospace industries owing to its lightweight and high strength, without compensating the safety and performance. In order to develop efficient Finite Element models of tubular elements which undergone prior forming processes, a constitutive material model should be utilized for aluminum alloy sheet to account for plastic anisotropy. The principal aim of the present article is to describe the significance of material anisotropy, and to determine various coefficients for material constitutive models in forming and crushing simulations. The uniaxial tensile tests have been performed to calculate yielding strength, ultimate tensile strength, strain hardening exponent, and anisotropy factor according to ASTM-E517 standard. As a result, the current paper highlighted the significance of utilizing constitutive material model which considers anisotropy, so as to obtain the accurate crashworthiness parameters of energy absorbing tubular structures during numerical simulations.

KEYWORDS: Crashworthiness, LS-DYNA, Energy Absorbers, Simulation, Anisotropy & Forming

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Original Article

1. INTRODUCTION

Nowadays, the use of new materials and innovative methods in the design and manufacturing of energy-dissipating elements has considerably increased the occupant safety and decreased the damage level to vehicles parts, fuel savings and gas discharge. In this context, thin-walled steel tubular structures had been extensively used, as these energy absorbers with either square or circular cross sections. Operation of these elements in automobile safety applications is comparable to the working principle of fuses in electronic circuit. To be precise, when a collision happens, these elements deform initially, absorb energy progressively and provide safety to the occupants, and hence play an important part in safeguard of passengers.

Another important role of energy absorber is to dissipate the impact kinetic energy by inelastic crushing in an event of sudden accidents to minimize the shock transmitted to the passengers, where the continuous in elastic deformation folding is developed. Light-weight and better collapse behavior have to be recognized from the demand of energy saving and safety, which is the main drawback in the steel tubular structure. Materials such as aluminium, magnesium and composites are good candidates for replacing mild steel. Among these, Aluminium is a good candidate and is the utmost desired ranges due to its ductility with outstanding energy dissipation ability and substantial light weight. When aluminium alloys are utilized as energy absorbing devices, weight saving to the range of 25–35% can be attained related to the traditional steel tubes

In recent decade, Light weight sheet metals are employed to fabricate crashworthy, fuel efficient and eco-friendly vehicles [1]. From the various literature studied from the previous years, it is obvious that lighter vehicles are nowadays produced by using aluminium sheet metal as body components instead of steel [2–4]. The introduction of aluminium sheet metal also helps the automotive manufacturers to produce fuel efficient vehicles. For such materials, the numerical modeling of plasticity has become significant as the strength is attained by its ductility during FE simulations [5, 6]. In practice, these structures are attained after many prior forming procedures, e.g. extrusion, rolling and welding, which enforce enormous deformations to the material [7, 8]. These processes might also produce anisotropic properties, which must be considered to characterize suitably the mechanical behavior of the processed material [9].

This induced anisotropy in the material contributes to the theory of orientation-dependent material properties like ductility, strain hardening, yield strength, and tensile strength [10]. As anisotropic characteristics of rolled metals is the serious concern and shows a substantial role to enhance the deformation characteristics, it is significant to develop a constitutive material model that accurately predicts the material behavior, when the metal sheet structure involved in collision happenings [11]. For crashworthiness applications, examination on the effect of this anisotropy is significant to ensure efficient modeling of structures. To develop material model with anisotropy behavior, first the basic elastic plastic material model should be determined at low strain rate for different grain orientation through experimentation [12]. Hence, in this study, uni-axial tensile tests were initially performed in all three rolling directions to determine the material properties of aluminium sheet metal material property input in the finite element simulation using LS-DYNA ®.

In the present article, the selection of materials for fabricating the proposed tubes and their chemical composition analysis are detailed initially. The subsequent section covers the development of an appropriate material model for numerical simulation and also provides the experimental procedure to determine the anisotropic coefficients and tensile properties of the aluminium alloy based on the ASTM standards.

2. MECHANICAL CHARACTERIZATION OF ALUMINIUM AA-6061 ALLOY

2.1 Aluminium AA6061 Alloy

Light weight sheet metals are nowadays used to fabricate crashworthy, fuel efficient and environment friendly vehicles. From the various literatures, it is obvious that lighter vehicles are nowadays produced by using aluminium sheet metals as body parts instead of steel. The introduction of aluminium sheet metal also helps automotive manufacturers to produce fuel efficient vehicles. For such aluminium alloys, the design of plasticity is essential as the strength is acquired at the outflow of ductility. In practice, these constituents are attained after numerous forming procedures, e.g. extrusion, rolling and forming processes, which enforce very huge deformations to the material. These procedures could lead to anisotropic properties, which could not be ignored every time if one needs to properly characterize the mechanical behavior of the formed material.

Aluminium AA6061 alloy is the widely employed heat-treatable extruded alloy owing to its strength capability, better toughness characteristics and excellent corrosion resistance [13–15]. In this study, commercially available aluminium AA6061alloy rolled sheets of 1.63 mm thickness were selected for the present study. This alloy material was selected owing to its outstanding formability characteristics and its common utilization in automotive body components, panels and airplane structures like wings and fuselages [16, 17].

2.2 Chemical Composition

A chemical examination test was performed using Optical Emission Spectrometer (OES) for quantifying the various elements exists in the aluminium rolled sheet based on the ASTM-E1251 standard [18, 19]. The sheet is composed of aluminium AA 6061 alloy and was received in annealed condition. Table 1lists the significant elements present in AA 6061 are magnesium (Mg), iron (Fe) and silicon (Si), and the other impurities present are manganese (Mn), copper (Cu), chromium (Cr), zinc, and titanium (Ti).

Table 1: Chemical Examination Results

Elements	Si	Fe	Cu	Mg	Zn	Mn	Cr	Ti	Al
Weight (in %)	0.62	0.54	0.14	0.42	0.12	0.066	0.04	0.009	98

2.3 Plastic Anisotropy towards Failure

Plastic forming is frequently employed to attain the ultimate profile of great strength aluminium alloy elements, through which the anisotropy of workability regularly developed. The anisotropy is termed as the variance between property values estimated along three axes, and probable to result in unpredicted material flow behavior. Therefore, it is important to expose the anisotropy of aluminium alloys during plastic forming operations, so as to accurately regulate the material flow pattern during material forming. It is significant that the anisotropy of aluminium alloys is predominantly affected by the crystallographic surface which progresses thru rolling and heat treatment operation, and the influence of crystallographic surface could be categorized into direct and indirect effects. Direct effects are recognized as the alignment of crystals and slip structures with relation to applied stresses and grain distribution.

2.4 Modelling of the AA6061-O Plastic Anisotropy

In Finite Element simulations, to model rolled sheet metal materials, which have anisotropic characteristics, the influence of anisotropy on the buckling results desired to be incorporated for accurate predictions. Anisotropy has a note worthy effect on the effective plastic strain distribution in sheet forming, and it is also related to thickness variations and formability [20, 21]. Hence the anisotropy of the rolled sheet must be properly incorporated for the accurate analysis of aluminium forming procedures. Numerous anisotropy constitutive models have been utilized for estimating the limiting strain or the formability of the sheet metals. Conversely, material constitutive models to envisage the limiting strain and fracture for aluminium alloys are inaccurate, owing to its challenging microstructure and work-hardening behavior. The Hill yield criterion is mostly employed owing to its easiness, but this criterion is insufficient to outline the plastic performance of materials like aluminium alloys [22, 23]. The Barlat criterion gives a virtuous estimation of the yield locus for aluminium alloys devoid of anisotropy [24]. Further, additions of this criterion have been described to remove some of its limitations [25–27].

2.5 Anisotropic Elasto-Plastic Material Behavior

When material is deformed, the stresses will start to build up in the material and then the material will go throughout elastic range. When the stresses overcome elastic limit, the material is said to be plastic range. Because of this material behavior, an elasto-plastic analysis is necessary in this thesis. For this reason, a short description of this analysis and hardening rule are given. At the beginning of crushing, when the material is deformed in the elastic range, strain abides by Hook's Law:

$$\sigma = E\varepsilon \tag{1}$$

Where, E is elastic modulus. For general case of loading the equation can be given as:

$$\sigma = {}^4C : \varepsilon \tag{2}$$

Where ${}^4C$ denotes the fourth order elastic stiffness tensor strain of the material, is the second order elastic strain tensor.

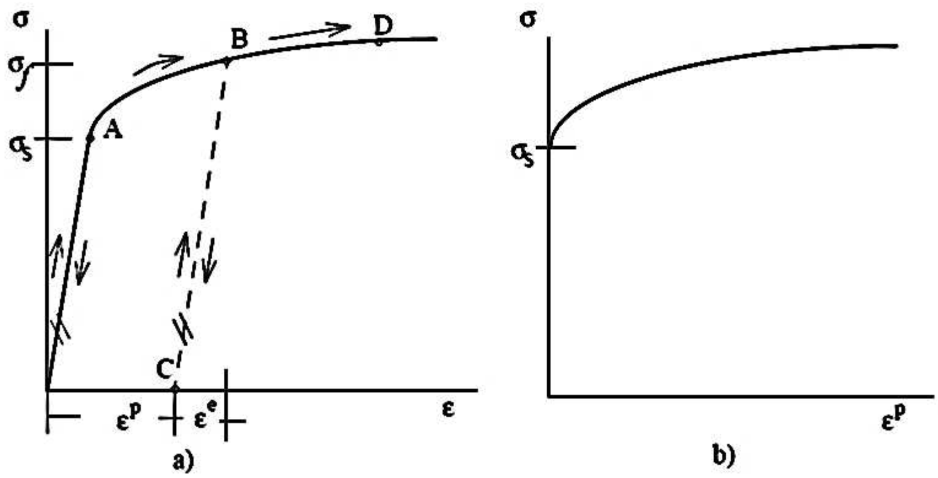

Figure 1: (a) The Elasto-Plastic Stress-Strain Diagram,
(b) The Responding Hardening Curve.

From the above figure, elasto-plastic material behavior will be understood obviously. As can be seen from figure 1 (a), Point A is considered as yield limit and the stress in there is called yield stress denoted by σ_s. The material respond to below this point is elastic; in this area unloading the material will be recovered completely as initial state. Only having elastic strain survives in this region (ε^e). Continuous loading exceeds point A until point B, unloading the strain will follow dash line in figure 1 (a). The elastic strain ε^e will be vanished and plastic strain is still retained in the material. At this state, the material will exist both kinds of strain: elastic strain ε^e and plastic strain ε^p. This is characteristic for an elasto-plastic regime. The material is deformed permanently. The maximum stress once imposed under plastic crushing, however, is recorded by the material and becomes the actual yield limit σ_f for additional plastic straining. Thus σ_f takes the place of the original σs when the specimen is unloaded and later reloaded.

$$\sigma_f = \sigma_f(\varepsilon^p) \text{ With } \sigma_f(0) = \sigma_s \tag{3}$$

The increasing of yield stress in this case is called strain hardening phenomena. In fact, forming is material modified process. Strain hardening phenomena will occur in this process. This is a positive effect of forming because it will make the structure significantly raise resistance of crushing mode.

2.6 Yield Function

A yield function is a substantial notion in the plasticity, which signifies the boundary of elastic distortions in a material exposed to any probable combination of stresses, and also could be designated as the onset of inelastic deformation indicator. It is employed along with an experimentally attained stress-strain curve as the material input data for computational simulations of the forming procedures. The yield surface and hardening law together could control the

constitutive equations which openly instigated to the numerical frameworks to define the material performance. To design the material buckling behavior in an improved manner, it is essential to incorporate each factor that could support the superior modeling capability.

The evolution of plasticity is determined using a yield surface. This surface is coupled to the loading history of the material through the use of a scalar history dependent parameter σ_s. The continuously updated history variable σ_s represents the most severe loading state to which the material point has been subjected in its loading history. The most general formulation is therefore

$$f(\sigma, \sigma_s) = 0 \tag{4}$$

The von mises yield function is represented for stress space as figure 2 below. The stresses vector ending inside the cycle are ascribed as elastic to states, $\varepsilon^p=0$. For the plastic states, the stresses vector will end on the cycle, $\varepsilon^p>0$, f=0. The state which is out of cycle is actually not gained in the elasto-plastic material.

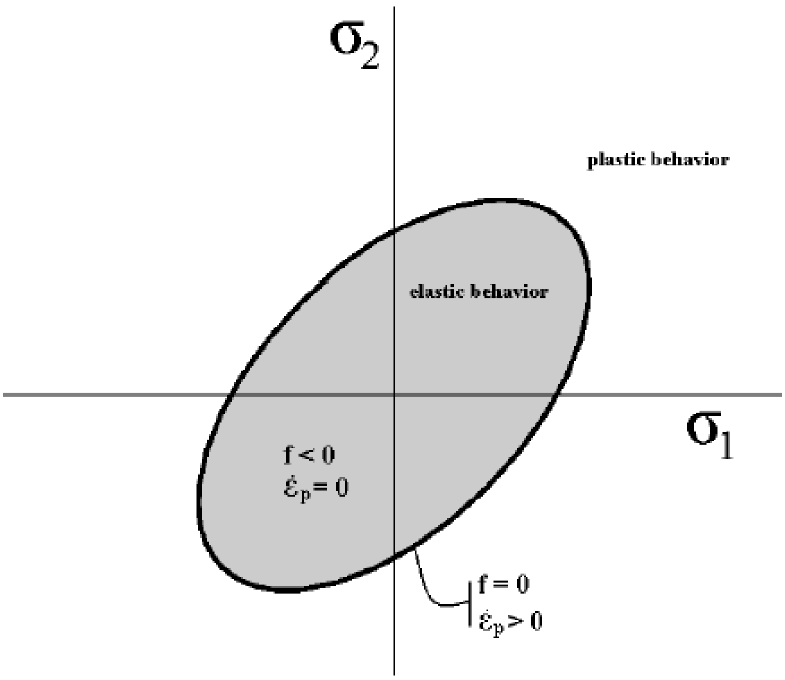

Figure 2: Von Mises Yield Loading Surface.

2.7 Barlat Yield Criterion

In practice, in the sheet metal forming process, the material is deformed under multi-axial loading. So, yielding may be generated by combination of stresses. Therefore, empirical flow rule is employed for prediction of combined stresses required to cause yielding under multi-axial loading conditions. Barlat and Lian (2005) established a yield criterion for anisotropic sheet metals with plane stress conditions. This material model employs the Lankford coefficients (R_0; R_{45} and R_{90}) for the description of anisotropy as follows:

$$f(\sigma) = a|K_1 + K_2|^M + a|K_1 - K_2|^M + c\,|2K_2|^M = 2\bar{\sigma}^M \tag{5}$$

Where $K_1 = \frac{\sigma_{zz}+h\sigma_\omega}{2}$, $K_2 = \sqrt{\left(\frac{\sigma_{zz}-h\sigma_\omega}{2}\right)^2 + \left(p\sigma_{xy}\right)^2}$, M, a, c, p and h are material properties.

Note that, for FCC materials, M= 8. Also, c = 2- a when, $\bar{\sigma} = \sigma_0$. Although the coefficients h and c can be determined based on either R- values (along 0 and 90°) or yield stresses ($\sigma_0, \sigma_{90} and \sigma_b$), the coefficient p in both cases is given by:

$$P = \left(\frac{2}{2a + 2^m c}\right)^{\frac{1}{M}} \frac{\sigma_0}{\tau} \tag{6}$$

Where τ is the shear stress.

The coefficients h and a in terms of R values are known by Equations

$$h = \sqrt{\frac{R_0}{(1+R_0)} \frac{(1+R_{90})}{R_{90}}} \tag{7}$$

$$a = 2 - 2\sqrt{\frac{R_0 R_{90}}{(1+R_0)(1+R_{90})}} \tag{8}$$

Figure 3 shows the comparison of yield loading surface of von mises and barlat yield criterion. The von Mises yield criterion is the extensively recognized yield criterion for isotropic materials but does not take the anisotropy of the materials into account. However, the metallic sheets exhibit anisotropic behavior characteristic of rolling process. Therefore, to account for the material anisotropy, Barlat proposed an anisotropic yield criterion, considering that the material has an anisotropic behavior along the three orthogonal symmetry planes.

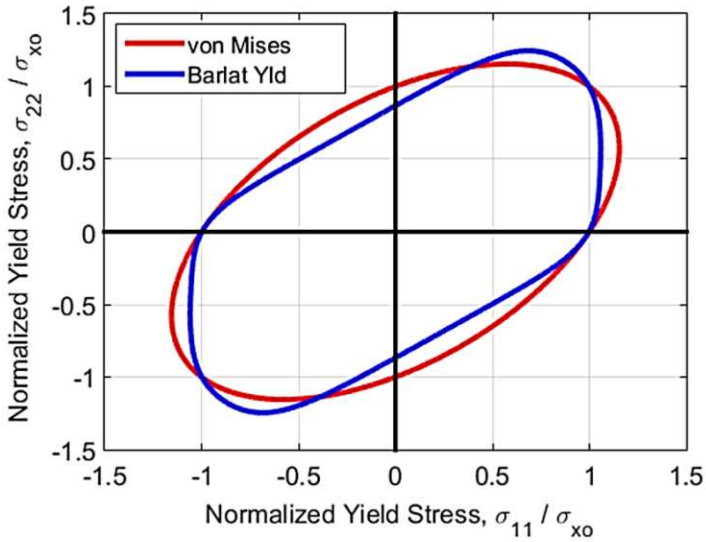

Figure 3: Yield Loading Surface Comparison.

2.8 Lankford Coefficient

Influence of various material coefficients like strain exponent, strength factor strain rate sensitivity, and anisotropy on the plastic behavior of the aluminium sheets was examined. It was observed that the strain exponent and anisotropy of the sheet extensively influence the formability of the material among all the other coefficients considered. The deviation of the material performance with direction could be evaluated by an extent termedas Lankford anisotropy coefficient, which is shown as

$$R = \varepsilon w / \varepsilon t \tag{9}$$

This parameter is evaluated by uniaxial tensile examinations on samples in the form of a stripcut along three directions of the sheet, where εw and εt are the strains in the width and thickness directions of the sample, respectively. The direction in which these coefficients are evaluated could be designated by a suffix (i.e., R_0, R_{45}, and R_{90}) for examination in the rolling, oblique, and lateral directions. By convention, the anisotropy coefficients are typically evaluated at 20% elongation for the comparison purpose.

2.9 Forming Limit Diagram (FLD)

In order to know if the product after sheet metal forming is fail or not, forming limit diagram is used. FLD is deliberated as significant tool to check quality of stamped parts. Each sheet metal has its own FLD which evaluates its formability, strain limit and forming region. The diagram is a combination of the two principle surfaces strain minor and major where major strain is represented vertically and minor strain is represented horizontally as shown in figure 4. For varying strain ratios, from pure shear to equi-biaxial tension, the forming limit curve (FLC) is plotted. Limit Curve (FLC) obtained from experimental observations of the material. The area above FLC is the area of failure. When the strain proportion is positive, alternatively i.e. positive minor strain, it represents stretching is perceived. In situation of negative strain proportion, i.e. negative minor strain, it represents that drawing is witnessed. It must be also perceived that the strains plotted are true strains.

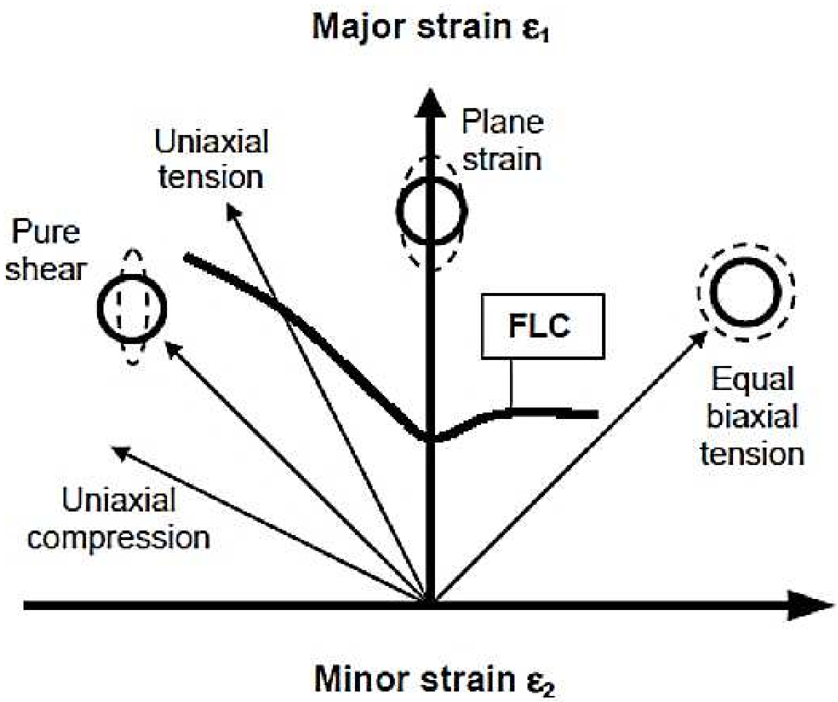

Figure 4: Forming Limit Diagram.

3. RESULTS AND DISCUSSIONS

In this study, the material used for fabricating the combined geometry tube samples was an aluminium alloy, AA 6061-O rolled sheets, generally used in the automobile manufacturing industries to fabricate body panels. As part of a study on the relationship between forming and crushing processes, constitutive material model for aluminium blank was developed for numerical analysis.

3.1 Determination of Tensile and Anisotropic Properties

To characterize the anisotropic properties, plastic flow and ductility of the material, uniaxial tensile tests were conducted on the commercial aluminium sheet. The experiments were done using 5kN Instron Universal Testing Machine subjected to displacement control with a speed of 5 mm/min. Strain gauge of 50mm gauge length was employed to determine the strain till fracture during deformation. Tensile test sample was taken from the aluminium sheet in the rolling direction (0°), based on ASTM E8 standard. The tested specimen is displayed in figure 5.

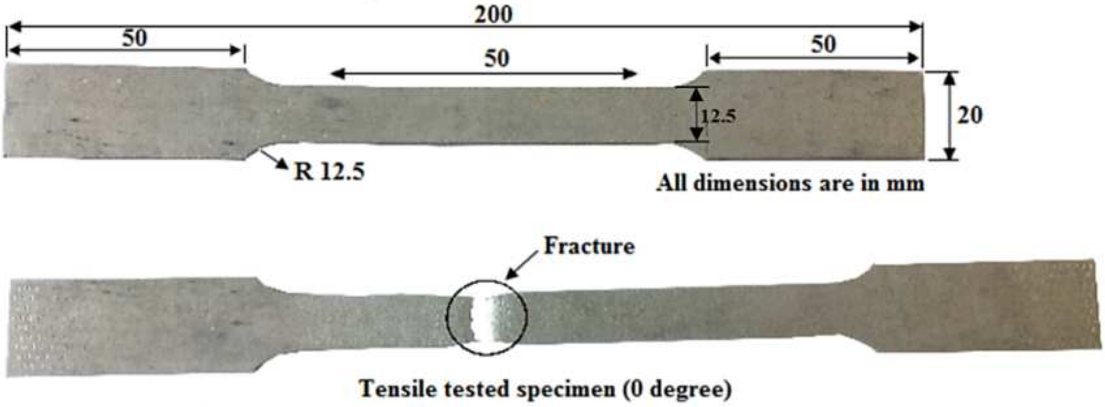

Figure 5: Tensile Test Specimen.

Anisotropy of the aluminium sheet was estimated in terms of plastic anisotropy proportion ''R'' which is the ratio of true strain(width)to true strain (thickness) of the sheet. R-bar tests were performed to determine the R in rolling (0°), inclined (45°) and transverse (90°) directions of the sheet according to the ASTM E517 standard. Dog bone-shaped specimens of desired dimensions were prepared from the aluminium sheet in 0º, 45º and 90º with respect to the rolling direction as shown in figure 6. Mechanical characteristics of the aluminium sheet determined from tensile and R-bar examinations are presented in Table 2.

Table 2: Results of Tensile and R Bar Test

Material	E (GPa)	μ	ρ (kg/mm³)	R_0	R_{45}	R_{90}	σ_y (MPa)	n	K (MPa)
Aluminium	68	0.3	2.7e-6	0.60	0.53	0.57	54	0.21	159

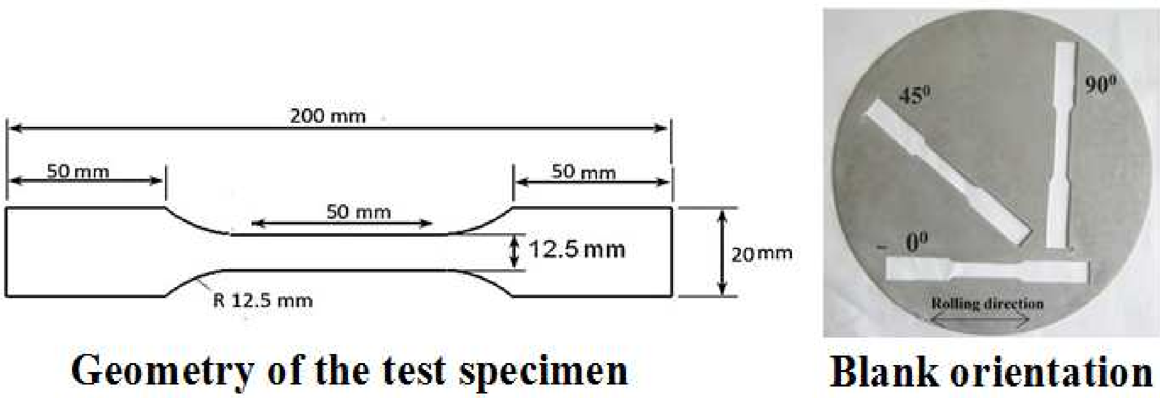

Figure 6: Specimen for R-Bar Test.

Table 2 presents the mechanical characteristics of the aluminium sheets determined from tensile and R bar tests. Where E is the modulus of elasticity, μ = Poisson's ratio, ρ = density, σ_y= yield stress, n = strain hardening exponent, K = strength coefficient and R_0, R_{45}, and R_{90}represents the anisotropy coefficients determined from tensile examinations at 0°, 45° and 90° with respect to the rolling direction respectively. The engineering stress strain curve of the aluminium specimen obtained from tensile test is displayed in figure 7. The values of engineering stress and engineering strain from tensile test are transformed into true stress and effective plastic strain, as displayed in the Figure 8 by the following relations (10) and (11).

$$\sigma_t = \sigma_{e(1+\epsilon_e)} \quad (10)$$

$$\epsilon_{pl.} = \ln(1 + \epsilon_e) - \frac{\sigma_t}{E} \quad (11)$$

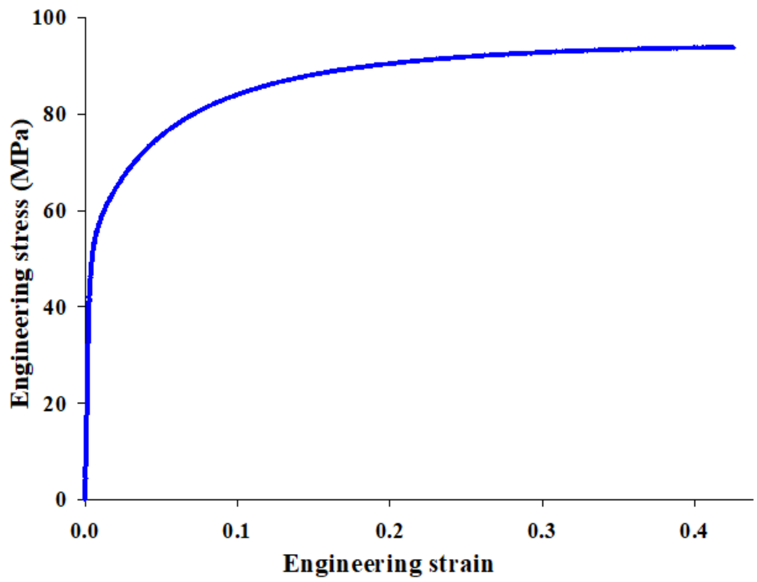

Figure 7: Engineering Stress-Strain Curve.

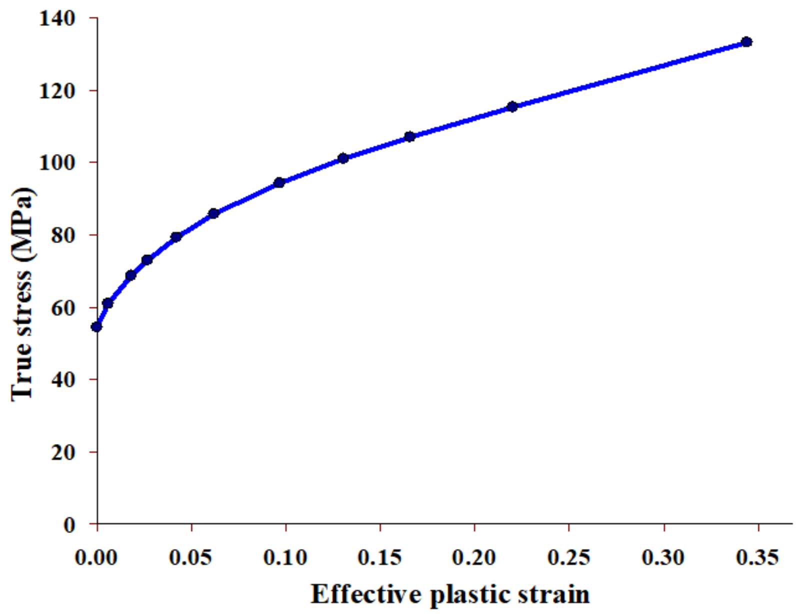

Figure 8: True Stress-plastic Strain Curve.

Where σ_e, σ_t, $\in_e$, and $\in_{pl.}$ are engineering stress, true stress, engineering strain and effective plastic strain respectively. The data attained was utilized for defining the true stress-plastic strain curve during the forming and crash simulations in LS-DYNA R-971®. The tensile properties of the selected aluminium 6061-O alloy determined from the tensile test and R-bar test were used in the material modeling during numerical simulation of both deep drawing process and crash simulation process.

4. CONCLUSIONS

In this research article, the significance of material anisotropy was described and the various coefficients for material constitutive models used in forming and crushing simulations were determined experimentally. The overall results revealed that the crashworthiness performance of the aluminium tubes strongly effected by anisotropy. The numerical simulation model incorporated with forming effects has been shown to provide better deformation behavior in formed tubes over conventional tubes. The influence of incorporating the material constitutive model in simulating the crushing performance of formed metal tubes resulted in an increase in the crushing force. The utilization of a material constitutive model considering anisotropy and forming effects, when investigating the axial crushing behavior of the tubular elements that have undergone forming processes is recommended.

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